REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

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1. REPORT DATE *(DD-MM-YYYY)* 24/09/91	2. REPORT DATE September 2001 (Final Report)	3. DATES COVERED *(From - To)* 12/15/95–09/30/00

4. TITLE AND SUBTITLE Non Traditional Transport Processes in Tunneling and Proximity Junctions	5a. CONTRACT NUMBER
	5b. GRANT NUMBER N00014-96-1-0258
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) M.R. Beasley	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Trustees of Leland Stanford Junior University Office of Sponsored Research 651 Serra Street Stanford, CA 94305-6215	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Office of Naval Research Electronics Div. 800 North Quincy Street Arlington, VA 22217-5000 Dr. Deborah Van Vechten	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSORING/MONITORING AGENCY REPORT NUMBER

12. DISTRIBUTION AVAILABILITY STATEMENT

Unlimited

20011010 071

13. SUPPLEMENTARY NOTES

14. ABSTRACT

Several project aimed at dealing with fundamental limitations in the present superconducting electronics technology based on Josephson junctions were carried out. The need for high resistance superconductor/normal metal/superconductor Josephson junctions was reiterated and some constraints on the more favorable technology were established. A phenomenological theory of Josephson coupling in high Tc superconductor/normal metal/superconductor junctions was developed. The practical considerations to develop a new concept for memory storage in superconducting electronics based on the superconductor/ferromagnet proximity effect were pursued.

15. SUBJECT TERMS

Josephson junctions, Tunneling via localized states, Superconductor/ferromagnetic proximity effect.

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON M.R. Beasley
a. REPORT	b. ABSTRACT	c. THIS PAGE	unlimited	8	
--------unclassified-----					19b. TELEPONE NUMBER *(Include area code)* (650)723-1196

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI-Std Z39-18

Final Report

to the Office of Naval Research

on a Program for

NON TRADITIONAL TRANSPORT PROCESSES IN

TUNNELING AND PROXIMITY JUNCTIONS

Principal Investigator

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September 2001

INTRODUCTION

Superconducting electronics based on the Josephson junction is the only technology that has speed and power characteristics vastly superior to those of silicon. Highly complex circuits with large device count have been successfully demonstrated. On the other hand, this technology has two serious problems that limit its extendibility. First, it is presently limited in ultimate speed by the need to provide an external resistive shunt in order to eliminate the hysteresis inherent in the switching characteristic of a tunneling Josephson junction. As we pointed out many years ago [1], this leads to the need to consider non-tunneling barriers in Josephson junctions. Second, the superconducting memory technology based on flux quantization in superconducting rings containing a Josephson junction is limited to relatively low-density memory, due to the inherently large size of the memory cells. Thus no cryogenic main memory technology compatible with Josephson junction logic exists. This ONR program was aimed principally at addressing these two problems. Also included was some final work on earlier projects.

SUMMARY OF PROJECTS AND RESULTS

Transport Via Localized States in Tunnel Barriers.

In previous work under ONR support we had developed a very good understanding of the role of localized states in transport through tunnel junctions [2]. The barrier used was amorphous silicon (a-Si) because it is known to contain a well-defined density of localized states. Under this program we examined some of our earlier work and documented empirically the manner in which the presence of these localized states leads to deterioration in the tunneling characteristic and a reduction on the Josephson coupling. Specifically, we examined the affect of the localized state on the I-V curve and the Josephson critical current of Nb/a-Si/Nb tunnel junctions as a function of junction thickness.

Experimentally we found that both the Josephson coupling and the single-particle tunneling characteristic deteriorated as the barrier thickness was increased. This is not surprising [3]. What was surprising was that this deterioration set in at a barrier thickness that was considerably smaller than that at which resonant tunneling or hopping via the localized states dominated the overall conductance of the junction. The physical mechanism of this deterioration is not understood.

The understanding of transport via localized states established in this program is now being used by those attempting to understand transport via barriers in the high Tc superconducting Josephson junctions, where the presence of localized states has been postulated.

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High Resistance SNS Proximity Coupled Josephson Junctions.

As noted in the introduction, in order to achieve in practice the full speed potential of Josephson junction electronics, one needs to use proximity coupled superconductor/normal metal/superconductor (SNS) Josephson junctions. The basic problem with this approach is to achieve a normal metal barrier with a high resistance. We had in earlier work under ONR support demonstrated that such junctions could be made by using N materials near a metal/insulator transition [1]. The material we used was an amorphous Nb-Si alloy.

From a simple-minded point of view, it should be possible to achieve an infinite resistance junction right at the M/I transition. In this program, we examined our earlier results to examine this possibility by looking at data from junctions with barriers very near the M/I transition. We found that it was not possible to achieve arbitrarily high resistances. The reason is clear. The physical mechanism of the M/I transition in many materials is due to the localization of the carriers. As is well established both theoretically and experimentally, this is a second order transition and therefore length scale dependent. Specifically, just on the insulating side of the transition, the material is insulating only at infinite length scales. Junction barriers are obviously of finite thickness, and therefore finite conduction remains at short length scales. In the language of phase transitions, the junctions are thinner than the coherence length of the localization process.

This phenomenon will limit the resistances that can be achieved in practical SNS Josephson junctions. Our results should provide a sound conceptual base to those presently attempting to develop high resistance SNS barriers for the high Tc superconductors and for the conventional high Tc superconductors that are of technological interest (i.e., NbN) [4].

Theory of Josephson Coupling in High Tc Josephson Junctions Using Cuprate Barriers.

Considerable success has been achieved making high Tc cuprate SNS Josephson junctions based on the use of "N" materials that are themselves a cuprate. There is no wide agreement on the electronic structure of these barriers, or on the nature of the Josephson coupling. One phenomenological theory of the high Tc superconductors postulates that both the superconducting and normal phases of these materials can be described in a unified way based on the notion of a 5 dimensional order parameter—the so-called SO(5) theory of high Tc superconductivity. Two dimensions describe the familiar superconducting (i.e., Ginzburg-Landau) order parameter, and the other three describe an assumed anti-ferromagnetic normal state. No other states are possible in this model. This raises the question of how Josephson coupling is achieved in this situation.

We have developed a model of Josephson coupling based on this theory that has a very unusual character [5]. The main difference arises when a phase shift of π exists across the junction. In a conventional Josephson junction the amplitude of the order parameter goes to zero at the center of the junction under this condition. In the SO(5) theory, the amplitude of the order parameter stays constant but rotates out of the

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superconducting plane into an anti-ferromagnetic direction. Other, more subtle differences also pertain.

The SO(5) theory in its pure form has been criticized, but other, ostensibly more realistic, theories also have the property that the superconducting and normal states are described by a unified order parameter. The nature of the Josephson coupling in these theories can be expected to be qualitatively similar to that which we worked out with in the SO(5) theory.

The experimental situation remains too murky to definitely test these ideas.

Superconductor/Ferromagnet Proximity Effect.

Under support of the DoD URI in Superconducting Electronics, we proposed a new memory cell concept based on the superconductor/ferromagnet (SF) proximity effect [6]. The principle of this device is based on the particular (oscillatory) spatial behavior of the superconducting order parameter that extends into a ferromagnetic material. Preliminary examination of the scaling properties of memory cells based on this concept indicate that they can be scaled easily to sub-micron dimensions.

In this program we considered in more detail the scaling properties of these memory cells. We find that they should be easily scalable down to sub-micron dimensions. Questions remain as to the ultimate switching speed of these devices, however. We also examined the materials parameters needed to achieve this affect in a useful device configuration. Specifically, we found that this requires a ferromagnetic material with a low Curie temperature and small spin-orbit scattering. The former ensures a long coherence length in the ferromagnetic material, and the latter ensures that the S/F proximity effect is not destroyed by excessive non-magnetic (i.e, spin-orbit) spin-flip scattering.

These issues were examined both theoretically and experimentally. Theoretically we assessed the spin-orbit scattering process in various real materials in which observation of the S/F proximity effect had been claimed [7]. Experimentally, we identified two materials that appear favorable for observing the oscillatory S/F proximity effect and, hence, for real device applications. The two materials identified were Ni-Cu alloys for low T_c applications and $SrRuO_3$ for high-T_c applications. Thin film deposition work has been successfully carried out on both of these materials in our laboratory. Significantly, success in demonstrating the oscillatory nature of the S/F proximity effect using these two materials systems has been claimed by other groups, indicating a favorable prognosis for this new device concept.

Some particular aspects of spin-dependent tunneling in superconductor/insulator/ ferromagnet junctions were also investigated as part of this program [8].

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Data for the period 15 December 1995 to 30 September 2000.

Grant No. N00014-96-1-0258

Program Officer: Dr. Deborah Van Vechten

Publications:

1. M. R. Beasley, "Transport via Localized States in MIM and SIS Tunnel Junctions," (invited paper), in *Hopping and Related Phenomena*, eds. O. Millo and Z. Ovadyahu, Racah Institute of Physics, the Hebrew University, Jerusalem, Israel. Proceedings of Conference, August 27-30, 1995, pp. 255-264.   Published, 1996.
   (Citations—no information)

2. E.A. Demler, G.B. Arnold, M.R. Beasley, "Superconducting proximity effects in magnetic metals," *Phys. Rev. B*. **55**, 15174-15182 (1 June, 1997). (Partial support.) (43 Citations)

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Invention Titles: 0

Patents Applied for: 0

Patents Issued: 0

Awards through ONR: 0

Technology transitions to industry: 0

Technology transitions to other DoD or US Govt. Agencies: 0

Number of doctorates: 1

Number of masters: 0

Citations = 103 Total